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Electrical performance analysis and economic evaluation of combined biomass cook stove thermoelectric (BITE) generator

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Abstract

The use of biomass cook stoves is widespread in the domestic sector of developing countries, but the stoves are not efficient. To advance the versatility of the cook stove, we investigated the feasibility of adding a commercial thermoelectric (TE) module made of bismuth-telluride based materials to the stove's side wall, thereby creating a thermoelectric generator system that utilizes a proportion of the stove's waste heat. The system, a biomass cook stove thermoelectric generator (BITE), consists of a commercial TE module (Taihuaxing model TEP1-1264–3.4), a metal sheet wall which acts as one side of the stove's structure and serves as the hot side of the TE module, and a rectangular fin heat sink at the cold side of the TE module. An experimental set-up was built to evaluate the conversion efficiency at various temperature ranges. The experimental set-up revealed that the electrical power output and the conversion efficiency depended on the temperature difference between the cold and hot sides of the TE module. At a temperature difference of approximately 150 °C, the unit achieved a power output of 2.4 W. The conversion efficiency of 3.2% was enough to drive a low power incandescent light bulb or a small portable radio. A theoretical model approximated the power output at low temperature ranges. An economic analysis indicated that the payback period tends to be very short when compared with the cost of the same power supplied by batteries. Therefore, the generator design formulated here could be used in the domestic sector. The system is not intended to compete with primary power sources but serves adequately as an emergency or backup source of power.

Keywords: Biomass; Thermoelectric; Economics; Conversion efficiency; Thermal energy

1. Introduction

Biomass has been extensively used as a fuel in many heating processes in developing countries. It is commonly recognized as one of the traditional fuels for domestic cook stoves. Because of the increasing emphasis on environmental protection, indoor air pollution has become of great concern (Ndiema et al., 1998). Biomass can mitigate carbon dioxide in the atmosphere (Yokoyama et al., 2000). In Thailand, two-thirds of all bio fuel is used in the domestic sector (Tanatvanit et al., 2003). Generally, a Thai style cook stove has relatively low efficiency (typically ranging from 11% to 18%) (Bhattacharya et al., 2002b). In order to overcome this major drawback, a large number of improved biomass fired stoves have been developed (Bhattacharya et al., 2002a). One such development, the thermoelectric (TE) power generation system, involves the use of a thermoelectric module that produces power when located on a stove-top. It is well known and could be useful in regions with unreliable electricity supply (Nuwayhid et al., 2003). The stove-top thermoelectric system produces a maximum power output of 100 W by using 36 thermoelectric modules at typical stove top temperatures of 250 °C.

In more recent developments a heat sink composed of a thermosyphonic heat pipe has been adopted to further improve the power output of the thermoelectric system (Nuwayhid and Hamade, 2005). These developments revealed that a commercially available thermoelectric

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Nomenclature

A	area of thermoelement, mm^2
L	length (also termed height) of thermoelement, mm
L_c	length (thickness) of solder/contact in module, mm
N	number of thermoelements per module
n	contact parameter, mm
P	power, W
r	contact parameter, dimensionless
T_h	hot side temperature of thermoelectric, K
T_c	cold side temperature of Thermoelectric, K
Z	thermoelectric figure of merit, K^{-1}

Greek symbols

α	thermoelectric material Seebeck coefficient, $V\,K^{-1}$
ρ	electric resistivity of thermoelectric material, Ω cm
η_{TE}	conversion efficiency

module could provide over 3 W of power with a temperature difference of 70–80 °C. Experiments have also been conducted on the side-walls of the cook stoves. Stove wall temperatures are likely to be in the range of 150–300 °C. Commercially available TE (compounds based on bismuth-telluride) modules are used over this temperature range; however, their potentially wide scale application has been limited to a few specialized applications due to their relatively low efficiency [typically around 5%] (Rowe, 1999). One exception is the TE recovery of waste heat in which it is unnecessary to consider the cost of the thermal input. Consequently, low conversion efficiency is not a serious drawback. The use of a TE converter for electrical power generation has conventionally followed the basic arrangement shown in Fig. 1. A TE module consists of several N and P pellets connected electrically in series and thermally in parallel sandwiched between two ceramic plates. The bottom plate is bound to a heat sink and the load is supplied with the proper polarity. The heat, which emanates from the source, flows through the top surface of the TE module. Electrical power is derived from the movement of electrical carriers brought on by heat flow through the TE pellets. Holes or positive carriers move to the heat sink side of P-type pellet resulting in a net negative charge at the heat sink side of the N-type pellet.

In this study, we consider the TE recovery of power typical of a biomass cook stove thermoelectric generator (BITE). Pertinent TE equations are presented. The equations were used to choose a suitable heat sink. Simple economic evaluations were discussed in order to encourage the advance of in situ TE power generation at the domestic user end.

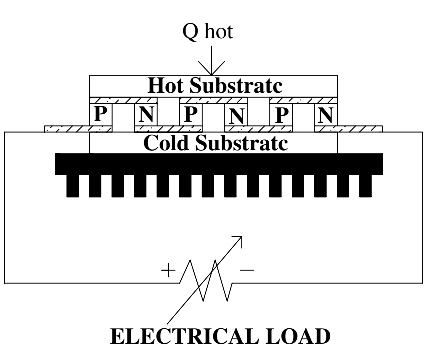

Fig. 1. TE module in power generation mode.

2. Methods

2.1. Theoretical model

The required power for application in this work is that it be sufficient to run a small electrical device such as a portable radio or a low power incandescent light bulb. From the manufacturing data of TE model TEP1-126–3.4 which is used in this prototype, the match load out power is 2.4 W with a temperature difference of 150 °C between hot side and cold side of the TE module.

Theoretically, the maximum power output of a realistic TE module takes into account the contact resistance and the conversion efficiency as given by Rowe and Min (1998).

$$P = \frac{\alpha^2}{2\rho}\frac{NA(T_h - T_c)^2}{(L+n)(1+2rL_c/L)^2} \quad (1)$$

$$\eta_{TE} = \left(\frac{T_h - T_c}{T_h}\right)\left\{(1+2rL_c/L)^2\left[2 - 0.5\left(\frac{T_h - T_c}{T_h}\right) + \frac{4}{ZT_h}\left(\frac{L+n}{L+2rL_c}\right)\right]\right\}^{-1} \quad (2)$$

Typically, $n = 0.1$ mm, $r = 0.2$, $L = 1.2$ mm, $L_c = 0.8$ mm, $\alpha = 2.1226\times10^{-4}\ V\,K^{-1}$, $N = 126$ couples, $\rho = 2.07\times10^{-3}\ \Omega$ cm, $Z = 2.75\times10^{-3}\ K^{-1}$ and $A = 1.96\ mm^2$.

2.2. Application and experimental set-up

The cook stove is used extensively throughout Northeast Thailand (Bhattacharya et al., 2002b). It is made of fire clay. It has an integrated grate with equally distributed holes of 15 mm diameter. Wood or charcoal can be burnt on the grate. All fuels can be ignited with kindling or kerosene. The stove weighs about 12 kg. The dimensions of the charcoal-wood stove are shown in Fig. 2. A metal sheet

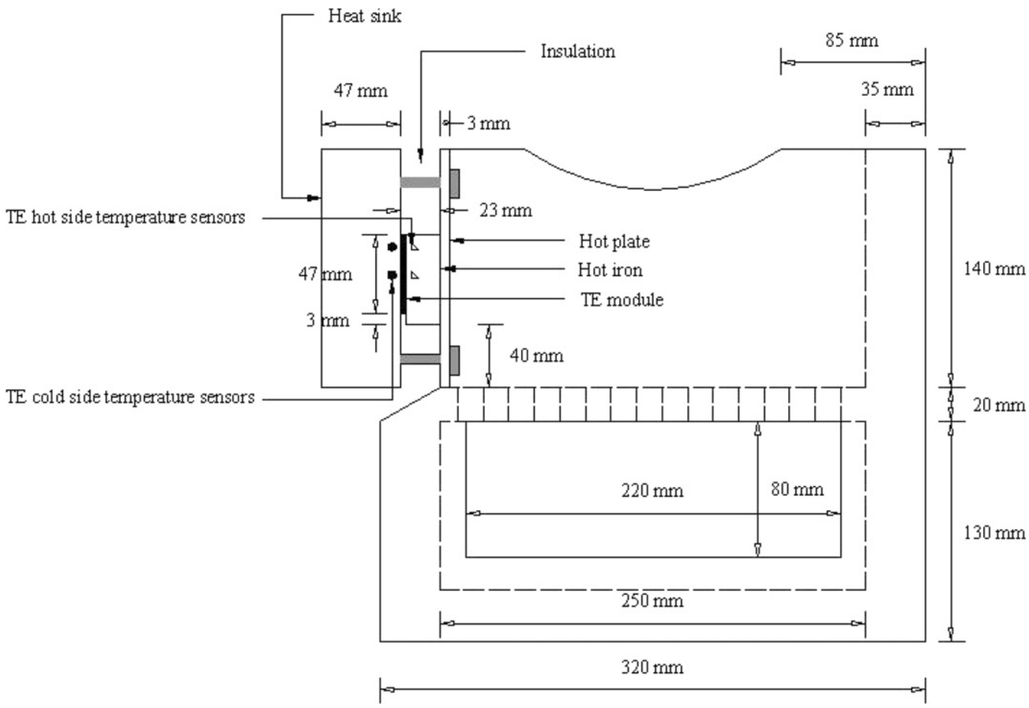

Fig. 2. Schematic representation of BITE and locations of temperature sensors.

was installed as one side of the stove wall. The hot side of TE module was installed on the middle of the metal sheet. The free convected air-cool fin heat sink used on the cold side was made of aluminum. The fins were 3 mm thick; 126.89 mm long in the vertical direction and had a height of 40 mm from the base with a fin space of 7.5 mm. The heat sink has a heat transfer coefficient (UA) of 1.1 W °C^{-1} (Cengel, 1998). Hence, the heat sink design can be made on the basis of the heat sink technology available in the local market. The space between the TE module, hot plate and heat sink was insulated using locally made ceramic fiber. The instrumentation in the experimental set up consisted of temperature sensors and electrical current and voltage measurements. A set of four chromel–alumel K-type (accuracy ±0.5 °C) thermocouples connected with a data logger (Testo 177–T4) was used for measuring the temperatures of hot side and cold side of the TE module as shown in Fig. 2. The output current and voltage were measured by a multi-meter (Fluke 189 accuracy VDC ± 0.025%, A ± 0.5%).

3. Results and discussion

3.1. Maximum power output

Changes in the power output according to the load resistance change with the temperature difference between the hot and cold sides of the TE module maintained at 150 °C (Fig. 3). The power output increases when the load increases. The maximum power output was detected at the match load of 2.4 W (Fig. 4). The power output obtained is nearly the power output of a standard thermoelectric module reported by Nuwayhid et al. (2003).

The I–V characteristics and power curve for a 150 °C temperature difference between the hot and cold sides of the TE module are shown in Fig. 4. The open-circuit voltage and the short-circuit current are 7 V and 0.9 A, respectively. As can be seen, the power curve is parabolic, with the maximum power output at half of the open-circuit voltage. This is due to the linear I–V characteristics. This emphasizes the importance of the internal resistance in determining the performance of a TE device.

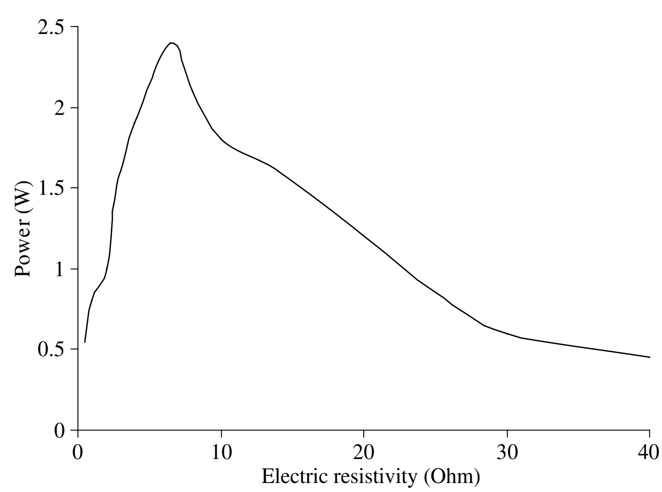

Fig. 3. Power change as a function of electric resistivity at the temperature difference 150 °C.

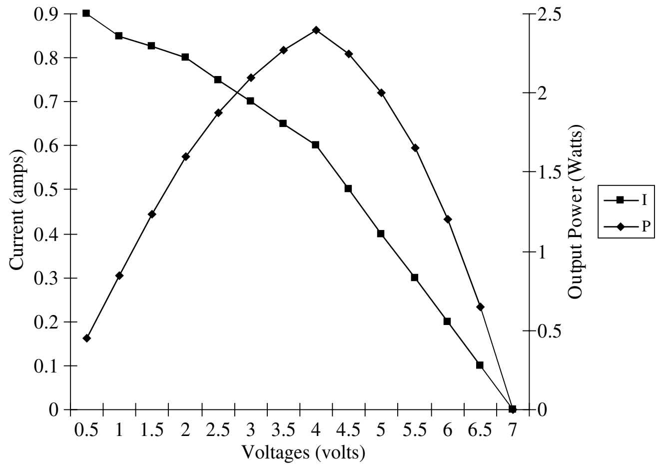

Fig. 4. Current–voltage characteristics and power output for hot and cold side temperatures of 240 °C and 90 °C, respectively.

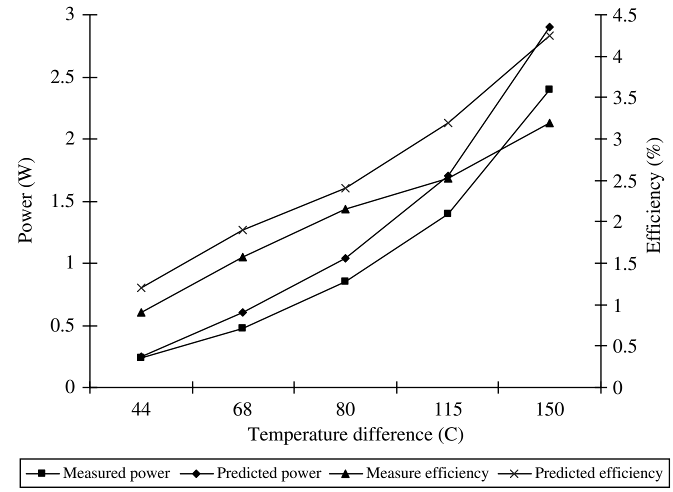

Fig. 6. Comparison between predicted and measured results.

3.2. Effect of hot side temperature on power output and conversion efficiency

The variation of the maximum power delivered into a match load with conversion efficiency at the maximum power point, as a function of hot side temperature is shown in Fig. 5. The maximum power and the conversion efficiency reached a maximum value at the hot side temperature of 240 °C. One of the factors that determine this maximum is the TE material itself, and its electron transport properties (Omer and Infield, 1998). The maximum power output obtained at a temperature difference of 150 °C was with an overall stove waste heat to electricity ratio of 3.2%.

3.3. Validation of the theoretical model

Data obtained from the experiment was used to validate the TE model presented. In Fig. 6 the predicted and measured power delivered into a matched load, and the corresponding conversion efficiency, as a function of temperature difference between hot and cold sides of the TE module are compared. It is apparent that while the predicted power performance continued to increase with the corresponding temperature difference increase, the measured performance reached a maximum value at a temperature difference of about 150 °C. This can be attributed to one primary factor. The power was proportional to the product of the square of the temperature difference and the square of the Seebeck coefficient, so that as the temperature difference increased, the term primarily determined the power output. The decrease in the Seebeck coefficient, which had been incorporated into the model and based on published data, was too small to compensate for this increase. However, at low temperatures, there was positive agreement between the predicted performance and measurement. Consequently, the level of agreement between the model and the measured data was encouraging and gave confidence in the accuracy of the model, at least under the operational conditions investigated.

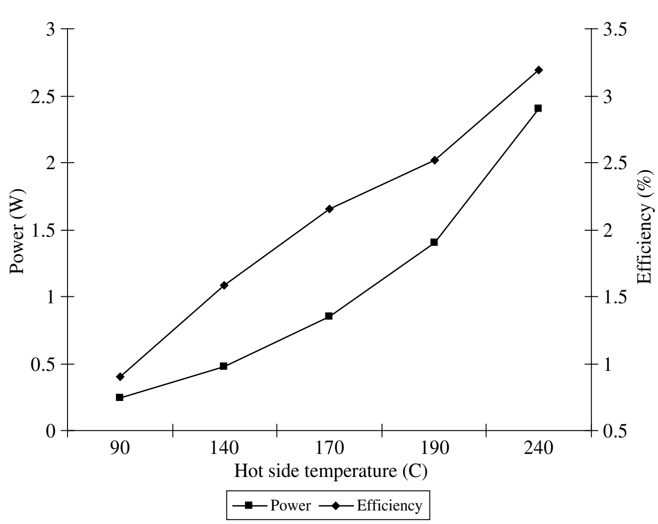

Fig. 5. Variation of BITE performance with hot side temperature.

3.4. Economic analysis

Cost analysis of the BITE was evaluated and compared with the cost of energy supplied (two batteries size AA, 1.5 V) to a 1.8 W load (an incandescent light bulb). Payback period was employed to determine the period of time required for the BITE to pay for itself by replacing purchased batteries. Payback period was defined as the time required for the BITE investment to equal the battery investment (Newnan, 1980). The payback period was confined to an analysis of battery replacement cost. No payback analysis was conducted to compare between the ongoing cost of primary power and BITE because the BITE system was not designed as a permanent replacement for primary power.

The conditions for evaluating the economic analysis are summarized in Table 1. During 2005, the interest rate of

Table 1
Conditions for economic evaluation

Item	BITE
Load (1.8 W)	Incandescent light bulb
First cost (US$)	60
Operating cost (US$)	–
Interest rate (%)	9
Life cycle	More than 15 years
Batteries (size AA, 1.5 V) cost (US$/h)	0.24

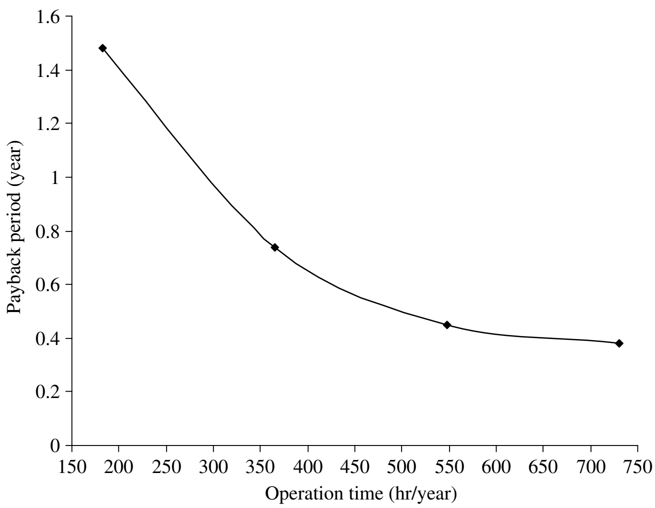

Fig. 7. Economic evaluation of the BITE (based on the operating time).

the Thai bank was approximately 9%. The economic evaluation of the BITE compared with the cost of energy supplied to a 1.8 W load at various operating time is shown in Fig. 7. It could be found that the payback period based on 365 h annual operating time of the BITE is 0.74 year. In addition, it can be noted that the higher the annual operating time, the higher the potential to use the BITE is obtained.

4. Conclusions

A thermoelectric generator for a biomass cook stove has been studied. The results showed that the BITE generates approximately 2.4 W at the temperature difference of 150 °C. This generated power is enough to run a small radio or a low power incandescent light bulb. In an environment of intermittent and uncertain electric supply, this makes sense and proves that a potential market does exist. Due to the simplicity and a continuous decrease of the cost of the TE modules, commercial development appears to be promising. The theoretical model adopted is able to predict the electrical power output and conversion efficiency, which were confirmed by the experiments in this study. Meanwhile, results show that the payback period of the BITE is 0.74 year, when compared with batteries supplying power to a 1.8 W load with an annual operating time of 365 h.

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